

12

EUROPEAN PATENT APPLICATION

21 Application number: 86107713.9

51 Int. Cl.⁴: G 06 F 12/08

22 Date of filing: 06.06.86

30 Priority: 28.06.85 US 750381

43 Date of publication of application:
04.02.87 Bulletin 87/6

84 Designated Contracting States:
CH DE FR GB IT LI NL SE

71 Applicant: Hewlett-Packard Company
Mail Stop 20 B-O 3000 Hanover Street
Palo Alto California 94304(US)

72 Inventor: Worley, William S.
19316 Falmouth Court
Saratoga CA. 95070(US)

72 Inventor: Bryg, William R.
18630 Perego Way
Saratoga CA. 95070(US)

72 Inventor: Baum, Allen
2310 Cornell Street
Palo Alto CA. 94306(US)

74 Representative: Liesegang, Roland, Dr.-Ing.
Sckellstrasse 1
D-8000 München 80(DE)

54 Cache memory consistency control with explicit software instructions.

57 Memory integrity is maintained in a system with a hierarchical memory using a set of explicit cache control instructions. The caches in the system have two status flags, a valid bit and a dirty bit, with each block of information stored. The operating system executes selected cache control instructions to ensure memory integrity whenever there is a possibility that integrity could be compromised.

21

1	DATA	PHYSICAL TAG	V	D
2				
3				
4				
.
.
.
n-1				
n				

31 33 35 37 39

Best Available Copy

FIG 2

HEWLETT-PACKARD COMPANY
Palo Alto, USA
EU 012 20

Telefon (089) 448 24 96
Telefax (089) 448 04 33
Telex 5214 382 pall d

Cache Memory Consistency Control with Explicit Software Instructions

7 Most modern computer systems include a central
8 processing unit (CPU) and a main memory. The speed at which
9 the CPU can decode and execute instructions to process data
10 has for some time exceeded the speed at which instructions
11 and operands can be transferred from main memory to the CPU.
12 In an attempt to reduce the problems caused by this
13 mismatch, many computers include a cache memory or buffer
14 between the CPU and main memory.

15 Cache memories are small, high-speed buffer memories
16 used to hold temporarily those portions of the contents of
17 main memory which are believed to be currently in use by the
18 CPU. The main purpose of caches is to shorten the time
19 necessary to perform memory accesses, either for data or
20 instruction fetch. Information located in cache memory may
21 be accessed in much less time than that located in main
22 memory. Thus, a CPU with a cache memory needs to spend far
23 less time waiting for instructions and operands to be
24 fetched and/or stored. For such machines the cache memory
25 produces a very substantial increase in execution speed.

26 A cache is made up of many blocks of one or more words
27 of data, each of which is associated with an address tag

28

1 that uniquely identifies which block of main memory it is a
2 copy of. Each time the processor makes a memory reference,
3 the cache checks to see if it has a copy of the requested
4 data. If it does, it supplies the data; otherwise, it gets
5 the block from main memory, replacing one of the blocks
6 stored in the cache, then supplies the data to the
7 processor. See, Smith, A. J., Cache Memories, ACM Computing
8 Surveys, 14:3 (Sept. 1982), pp. 473-530.

9 Optimizing the design of a cache memory generally has
10 four aspects:

- 11 (1) Maximizing the probability of finding a memory
12 reference's target in the cache (the hit ratio),
- 13 (2) minimizing the time to access information that is
14 indeed in the cache (access time),
- 15 (3) minimizing the delay due to a miss, and
- 16 (4) minimizing the overheads of updating main memory
17 and maintaining multicache consistency.

18 All of these objectives are to be accomplished under
19 suitable cost constraints and in view of the inter-
20 relationship between the parameters.

21 When the CPU executes instructions that modify the
22 contents of the current address space, those changes must
23 eventually be reflected in main memory; the cache is only a
24 temporary buffer. There are two general approaches to
25 updating main memory: stores can be transmitted directly to
26 main memory (referred to as write-through or store-through),
27 or stores can initially modify the data stored in the cache,

28

1 and can later be reflected in main memory (copy-back or
2 write-to). The choice between write-through and copy-back
3 strategies also has implications in the choice of a method
4 for maintaining consistency among the multiple cache
5 memories in a tightly coupled multiprocessor system.

6 A major disadvantage to the write-through approach is
7 that write-through requires a main memory access on every
8 store. This adds significantly to the relatively slow main
9 memory traffic load which slows the execution rate of the
10 processor and which the cache is intended to minimize.
11 However, when write-through is not used, the problem of
12 cache consistency arises because main memory does not always
13 contain an up-to-date copy of all the information in the
14 system.

15 Input and output between the main memory and peripheral
16 devices is an additional source of references to the
17 information in main memory which must be harmonized with the
18 operation of cache memories. It is important that an output
19 request stream reference the most current values for the
20 information transferred. Similarly, it is also important
21 that input data be immediately reflected in any and all
22 copies of those lines in memory.

23 There have been several approaches to solving this
24 problem. One is to direct the I/O stream through the cache
25 itself. This method is limited to single processor systems.
26 Further, it interferes significantly with the processor's
27 use of the cache, both by keeping the cache busy when the

28

1 processor needs it and by displacing blocks of information
2 currently being used by the processor with the blocks from
3 the I/O stream. Thus it degrades both the cache access time
4 and the hit rate. An alternate approach is to use a write-
5 through policy and broadcast all writes so as to update or
6 invalidate the target line wherever found. Although this
7 method accesses main memory instead of the cache, it suffers
8 from the disadvantages of the write-through strategy
9 discussed above. In addition, this hardware intensive
10 solution is expensive to implement and increases the cache
11 access cycle time by requiring the cache to check for
12 invalidation. This is particularly disadvantageous in
13 multiprocessor systems because every cache memory in the
14 system can be forced to surrender a cycle to invalidation
15 lookup whenever any processor in the system performs a
16 store.

17 Another alternative is to implement a directory to keep
18 track of the location and status of all copies of each block
19 of data. The directory can be centralized in main memory or
20 distributed among the caches, I/O channels and main memory.
21 This system insures that at any time only one processor or
22 I/O channel is capable of modifying any block of data. See,
23 Tang, C.K., Cache Design in the Tightly Coupled
24 Multiprocessor System, AFIPS Proc., N.C.C., vol. 45, pp.
25 749-53 (1976). The major disadvantage of the directory
26 control system is the complexity and expense of the
27 additional hardware it requires.

1 Finally, if a processor fails, for instance because of
2 a power interruption, the memory system must assure that the
3 most current copies of information are stored in main
4 memory, so that recovery can be more easily accomplished.

5 It is an object of this invention to provide a system
6 for maintaining the memory integrity and consistency in a
7 computer system having cache memories, placing the burden of
8 maintaining integrity on the software, thus allowing the
9 hardware to remain relatively simple, cheap and fast.

10 It is also an object of this invention to minimize the
11 impact of the overhead for maintaining memory integrity and
12 consistency on the operation of the cache memories, so that
13 the cache access time and miss ratio can be minimized.

14 These and other objects of the invention are
15 accomplished in a computer having an instruction set
16 including explicit instructions for controlling the inval-
17 idation or removal of blocks of data in the cache memories.
18 Each block of data stored in the caches has two one-bit
19 status flags, a valid bit to indicate whether the block
20 contains up-to-date information, and a dirty bit to indicate
21 whether the data in the block has been stored to by the
22 processor since it entered the cache. The instruction set
23 includes instructions for removing a block with a particular
24 address from the cache and writing it back to memory if
25 necessary, for removing a block without writeback to main
26 memory, for suspending execution of instructions until
27 pending cache control operations are completed, and for

1 efficiently removing and writing back to main memory all
2 "dirty" blocks in the cache in case of a processor failure.
3 The operating system software invokes these instructions in
4 situations which could result in inconsistent or stale data
5 in the cache memories.

6
7
8
9 Figure 1 is a schematic block diagram of a computer
10 system which incorporates the invention.

11 Figure 2 is a schematic illustration of a cache memory
12 constructed in accordance with the invention.

13 Figure 3 is a schematic illustration of an alternative
14 form of cache memory constructed in accordance with the
15 invention.

16
17
18
19
20 A computer system which operates according to the
21 invention is schematically illustrated in Figure 1. The
22 main processor 11, often referred to as the CPU,
23 communicates with main memory 13 and input/output channel 15
24 via memory bus 17. The main processor includes a processor
25 19 which fetches, decodes and executes instructions to
26 process data. Data and instructions are stored in main
27 memory 13, transferred to processor 19 when they are
28

1 requested during the execution of a program or routine and
2 returned to main memory 13 after the program or routine has
3 been completed.

4 Access to main memory 13 is relatively slow compared
5 with the operation of processor 19. If processor 19 had to
6 wait for main memory access to be completed each time an
7 instruction or data was needed, its execution rate would be
8 reduced significantly. In order to provide access times
9 which more closely match the needs of the processor, cache
10 21, which may be referred to as a buffer memory, stores a
11 limited number of instructions and data. Since cache 21 is
12 much smaller than main memory 13 it can be economically
13 built to have higher access rates.

14 The operating system software for the computer, rather
15 than the hardware of the component units, is responsible for
16 maintaining the integrity and consistency of the memory. In
17 order to accomplish this, the operating system invokes
18 explicit control instructions included in the computer's
19 instruction set.

20 To explain the system of the invention more completely,
21 an understanding of the structure of cache memory 21 is
22 necessary. The entries of the array in cache memory 21 are
23 illustrated in Figure 2. Cache 21 comprises an array of
24 locations labeled with an index 31 which store data 33 and a
25 physical page tag 35 which corresponds to the physical page
26 number of the location of the copy of the data in main
27 memory.

1 In addition to the data 33 and tags 35 stored in the
2 cache, each block has associated with it two one-bit status
3 flags, "valid" and "dirty". The valid bit 37 is set if and
4 only if that block has valid data, i.e., up-to-date data.

5 The dirty bit 39 is set if the processor has stored to
6 the address since it has been brought into the cache.
7 Unless cache 21 updates main memory 13 every time processor
8 19 does a store (write-through), the cache has more up-to-
9 date data for a block than main memory has. Dirty bit 39
10 serves to indicate that main memory 13 must be updated by
11 writing the data in the block in cache 21 back to main
12 memory 13 when the block is swapped out of the cache.

13 Cache 21 can also be divided into two sections, one for
14 data and another for instructions, as illustrated in Figure
15 3. For many computer architectures, this split cache
16 provides performance advantages. Both the instruction cache
17 41 and the data cache 51 have structures similar to that of
18 the unified cache described above. Instruction cache 41 has
19 an array of locations labeled with an index 43. Each
20 location stores an entry comprising: a physical page tag
21 45, an instruction 46 and a valid bit 47. Data cache 51
22 has an array of locations labelled with an index 53. Each
23 location stores an entry comprising: a physical tag 55, a
24 block of data 56, a valid bit 57 and a dirty bit 58.
25 Although this cache organization provides certain
26 advantages, it also requires additional control instruc-
27 tions. In particular, instructions may be modified and
28

1 copies may then appear in both sections of the cache. The
2 operating system must therefore flush blocks from the
3 instruction cache 41 and from data cache 51 back to main
4 memory 13 to insure consistency.

5 The operating system performs the required memory
6 maintenance functions using six instructions: Flush Data
7 Cache, Purge Data Cache, Flush Instruction Cache, Flush Data
8 Cache Entry, Flush Instruction Cache Entry and Synchronize
9 Caches.

10 The Flush Data Cache (FDC) instruction sets the
11 addressed data cache valid bit to "invalid" if the data
12 address hits the data cache. The block of data at the given
13 address is removed from the cache and written back to the
14 main memory if the dirty bit is set.

15 The Purge Data Cache (PDC) instruction sets the
16 addressed data cache valid bit to "invalid" if the data
17 address hits the cache. The block of data at the given
18 address is removed from the cache and no write-back is
19 performed.

20 The Flush Instruction Cache (FIC) instruction sets the
21 addressed instruction cache valid bit to "invalid" if the
22 address hits the cache. The instruction at the given
23 address is removed from the cache.

24 The Flush Data Cache Entry (FDCE) instruction is a
25 special kind of flush that can be used in a routine to flush
26 the entire cache, for example in the event of a processor
27 failure. This routine is implementation dependent. For a

28

1 multiple-set cache, the routine steps through the index
2 range of cache once for each set. The FDCE instruction
3 flushes a block of data and sets the addressed data cache
4 valid bit to "invalid" whether or not there is a hit at the
5 cache index. That is, the block is written back to main
6 memory if and only if it is valid and dirty, without
7 comparing the cache tag to any requested address.

8 The Flush Instruction Cache Entry (FICE) instruction
9 accomplishes the same function in the instruction cache as
10 the FDCE instruction accomplishes in the data cache.

11 The Synchronize Caches (SYNC) instruction suspends
12 instruction execution by the processor until the completion
13 of all instruction cache and data cache operations. This
14 guarantees that any reference to data will await the
15 completion of the cache operations required to ensure the
16 integrity of that data.

17 The operation of the system is illustrated by the
18 following examples. The operating system controls access to
19 main memory by the processor and by the peripheral devices
20 attached to I/O channel 15.

21 When data is to be read into main memory 13 from an
22 external device through I/O channel 15, the operating system
23 must insure that the addresses into which or from which the
24 data is transferred do not overlap areas mapped into either
25 data or instruction caches. In order to clear any stale
26 data out of the caches, before the I/O is performed, the
27 system broadcasts to each cache the FDC and FIC instruction

1 over the range of addresses into which the input data is to
2 be mapped.

3 When data is to be read out of main memory to an
4 external device through I/O channel 15, the operating system
5 must insure that the addresses from which the data is
6 transferred do not overlap areas mapped into data caches, so
7 that the most up-to-date data is transferred. In order to
8 update main memory with the data in the caches that has been
9 modified by the processors, the system broadcasts to each
10 cache the FDC instruction for the range of addresses from
11 which the output data is to be read. The FDC instruction
12 causes the cache to write any dirty blocks back to main
13 memory.

14 In a virtual memory system, whenever a page or segment
15 is moved from main memory 13 to a peripheral memory (eg., a
16 disc memory) connected to I/O channel 15, the data from the
17 page or segment must be flushed from all caches. The
18 operating system broadcasts to the caches the FDC and FIC
19 instruction over the range of addresses included in the page
20 or segment. When a page or segment is destroyed, for
21 example because of program termination, the data must be
22 removed from the cache but need not be stored. In this
23 instance, the operating system uses the PDC and FIC
24 instructions. No flush or purge operations are needed when
25 a page or segment is created or brought in from a peripheral
26 memory because the addresses into which it is mapped will
27 have just been flushed or purged during the removal of the
28

1 previous page or segment to make room for the new page or
2 segment.

3 In order to accommodate programs with self-modifying
4 code, the operating system must remove from the caches any
5 stale copies of the modified instruction to guarantee that
6 only the new version of the instruction will be executed.
7 After the modification of the instruction has been done in
8 data cache 51, the operating system uses the FDC instruction
9 to force the modified copy out to main memory, uses the FIC
10 instruction to remove any stale copy of the instruction from
11 instruction cache 41, then executes the SYNC instruction to
12 insure that the modified instruction is not invoked until
13 the FDC and FIC instructions have been completed.

14 In the event of a processor failure, for example caused
15 by a power failure, the modified blocks of data residing in
16 the caches must be written back to main memory. The
17 operating system can accomplish this in a minimal amount of
18 time with the FDCE and FICE instructions. A routine using
19 the FDCE and FICE instructions flushes the caches quickly
20 because by stepping through the index range of the caches
21 rather than using the address space which is much larger.
22 As the routine steps through the caches, only the blocks
23 that are valid and dirty are written back to main memory 13.

Claims

1. A computer system having a multi-level memory hierarchy and means for maintaining the integrity of the blocks of information stored at different levels in the hierarchy, c h a r a c t e r i z e d
5 by
a processor (19) for executing instructions and processing data;
memory (13) for storing instructions and data;
an I/O channel (15) connected to the memory
10 (13) for transferring data and instructions into and out of the memory (13);
a cache (21) connected between the processor (19) and the memory (13) for storing selected blocks of information from the memory (13) for
15 use by the processor (19), and having associated with each stored block a valid status flag and a dirty status flag;
a set of instructions for providing explicit control of the removal of blocks of data from
20 the cache (21); and
an operating sytem capable of causing the execution of certain of the instructions from the instruc-
tion set to ensure the consistency of the informa-
tion stored in the cache (21) with the information
25 transferred into and out of memory (13).
2. Computer system according to claim 1, c h a r a c-
t e r i z e d in that the instruction set com-
prises Flush Data Cache, Purge Data Cache, Flush
30 Instruction Cache, Flush Data Cache Entry, Flush
Instruction Cache Entry and Synchronize Caches
instructions; and in that prior to transfer
of data or instructions into or out of memory
(13) via the I/O channel (15), the operating
35 system broadcasts the Flush Data Cache and Flush
Instruction Cache instructions to the cache

(21) over the range of addresses into which or out of which data is transferred.

3. Computer system according to claim 2, c h a r a c-
5 t e r i z e d in that virtual memory (13) is
used; in that, when a page or a segment is
removed from memory (13), the operating system
broadcasts the Flush Data Cache and Flush Instruc-
tion Cache instructions to the cache (21) over
10 the range of addresses in the page or segment;
and in that, when a page or segment is destroyed,
the operating system broadcasts the Purge Data
Cache and Flush Instruction Cache instructions
to the cache (21) over the range of addresses
15 in the page or segment.
4. Computer system according to claim 2 or 3,
c h a r a c t e r i z e d in that the cache
(21) is divided into two segments (41,51), a
20 data cache (51) for storing data and an instruction
cache (41) for storing instructions; that instruc-
tions can be modified when stored as part of
a block of data in the data cache (51); and :
in that after modification of an instruction,
25 the operating system issues the Flush Data Cache
instruction to the data cache (51) for the address
of the block including the modified instruction,
issues the Flush Instruction Cache instruction
to the instruction cache (41) for the address
30 of the modified instruction and then executes
the Synchronize Caches instruction.
5. Computer system according to any of claims 2
to 4, c h a r a c t e r i z e d in that
35 in the event of a processor failure, the operating
system executes a routine including the Flush
Data Cache Entry and Flush Instruction Cache

Entry instructions over the index range for the data cache (51) and for the instruction cache (41).

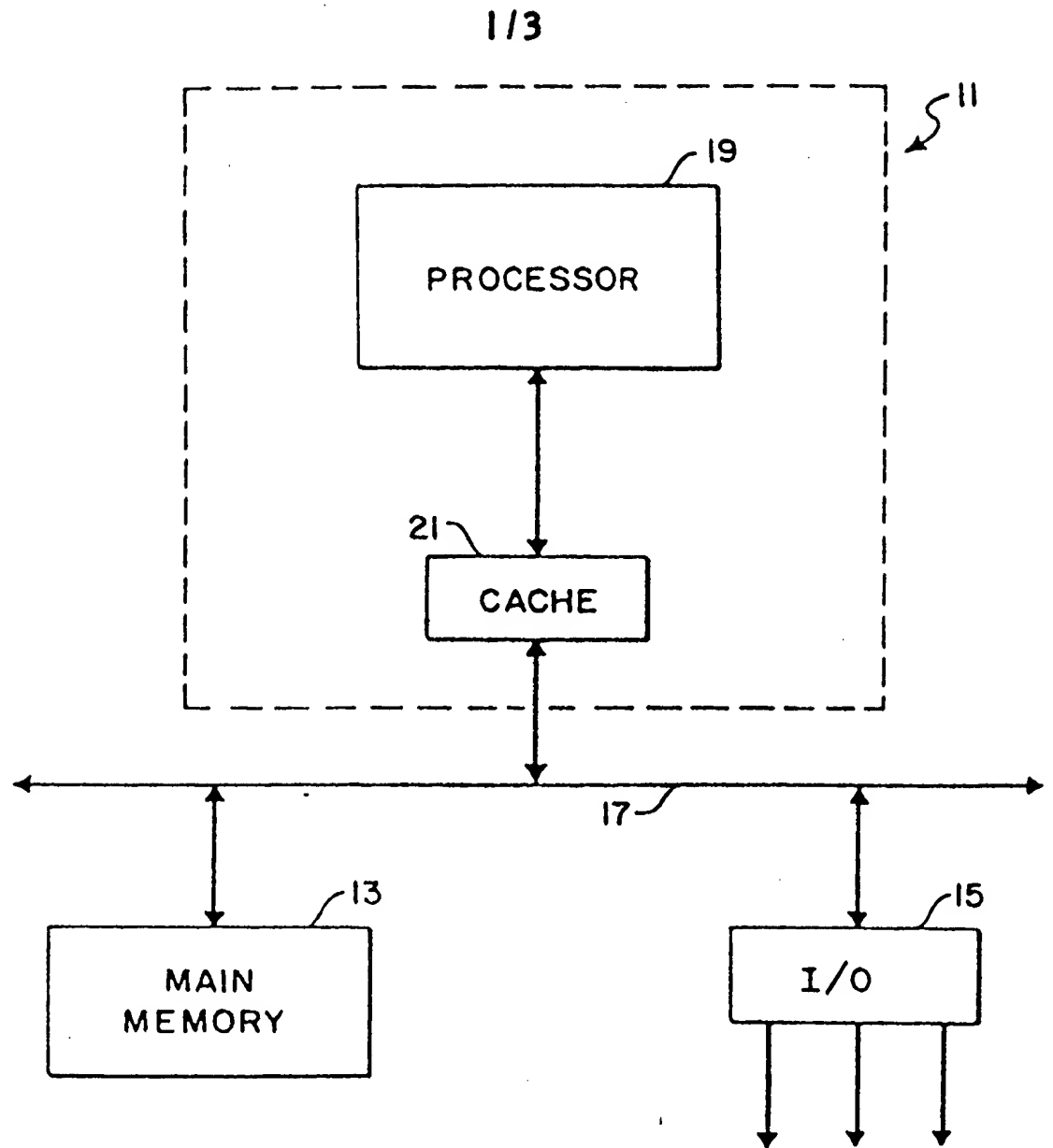


FIG 1

2/3

21 ↘

1	DATA	PHYSICAL TAG	V	D
2				
3				
4				
.
.
.
n-1				
n				

31 33 35 37 39

FIG 2

3/3

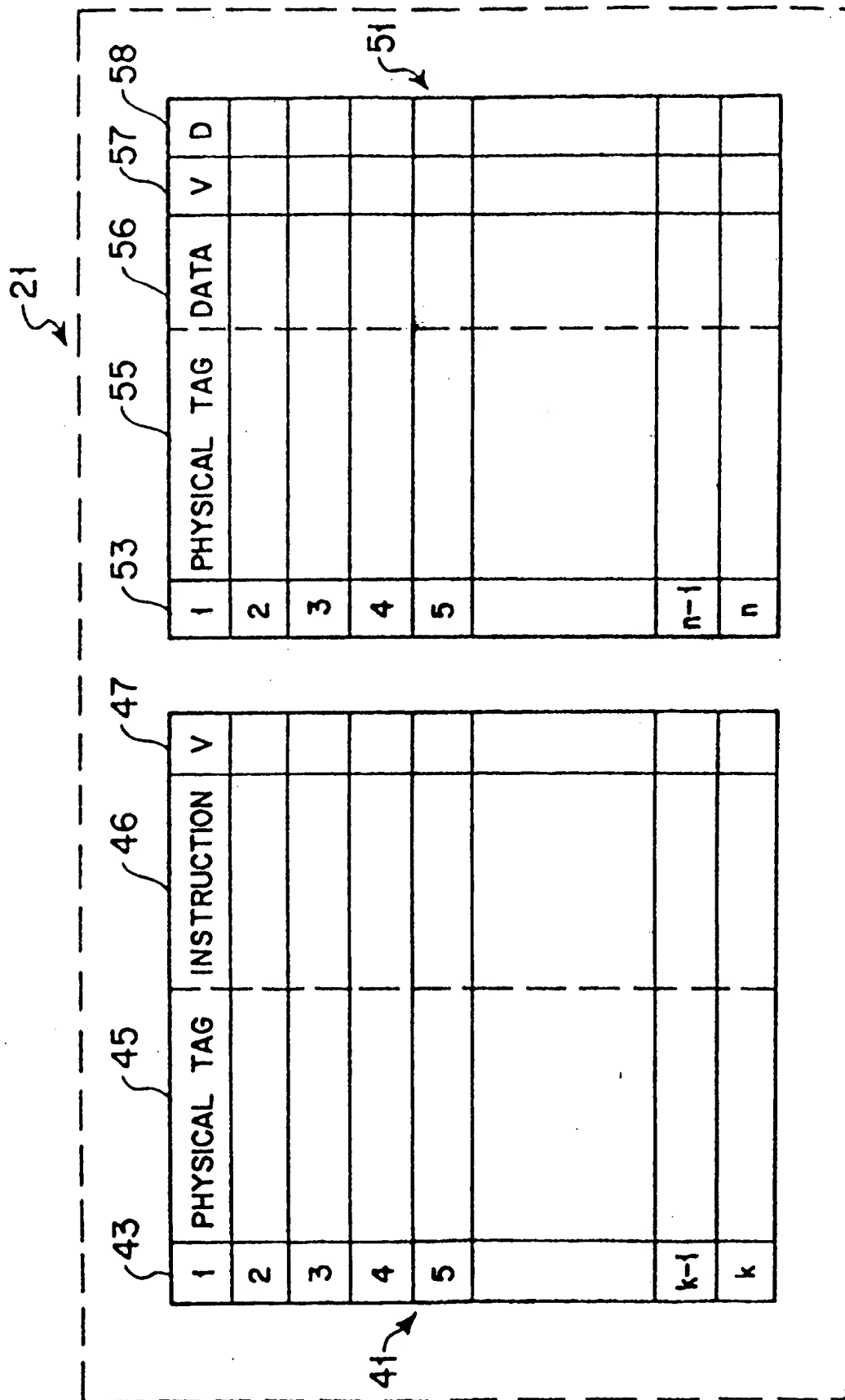


FIG 3



European Patent
Office

EUROPEAN SEARCH REPORT

0210384

Application number

EP 86 10 7713

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
Y	US-A-3,771 137 (BARNER et al.) * Figures 1-3; column 3, line 49 - column 5, line 52 *	1	G 06 F 12/08
A	---	4	
Y	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 24, no. 7A, December 1981, pages 3128, 3129, New York, US; J.F. COURT et al.: "Technique for improved channel performance" * Whole document *	1	
A	IDEM	2	
A	---	2, 3, 5	TECHNICAL FIELDS SEARCHED (Int. Cl. 4)
	US-A-3 845 474 (LANGE et al.) * Figure 8; column 11, line 38 - column 12, line 41 *		G 06 F 12/08
A	---	1, 2	
	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 23, no. 7B, December 1980, page 3329, New York, US; B.B. MOORE et al.: "Vary storage physical on/off-line in a non-store-through cache system" * Whole document *		
	---	-/-	
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 02-10-1986	Examiner LEDROUT P.
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons A : member of the same patent family, corresponding document	



European Patent
Office

EUROPEAN SEARCH REPORT

0210384

Application number

EP 86 10 7713

Page 2

DOCUMENTS CONSIDERED TO BE RELEVANT			Page 2
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
A	CONFERENCE PROCEEDINGS OF THE 11TH ANNUAL SYMPOSIUM ON COMPUTER ARCHITECTURE, Ann Arbor, Michigan, US, 5th-7th June 1984, pages 348-354, IEEE, New York, US; M.S. PAPAMARCOS et al.: "A low-overhead coherence solution for multiprocessors with private cache memory" * Pages 348-350 *	1	
A	--- EP-A-O 145 594 (FUJITSU) * Figure 3; page 5, line 12 - page 7, line 17 *	2,4	
A	--- EP-A-O 052 370 (HITACHI) * Figure 1; page 13, line 12 - page 15, line 11 *	2,4	
			TECHNICAL FIELDS SEARCHED (Int. Cl. 4)
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 02-10-1986	Examiner LEDROUT P.
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ BLACK BORDERS
- ☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES
- ☐ FADED TEXT OR DRAWING
- ☐ BLURRED OR ILLEGIBLE TEXT OR DRAWING
- ☐ SKEWED/SLANTED IMAGES
- ☐ COLOR OR BLACK AND WHITE PHOTOGRAPHS
- ☐ GRAY SCALE DOCUMENTS
- ☒ LINES OR MARKS ON ORIGINAL DOCUMENT
- ☐ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY
- ☐ OTHER: _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.